

I. INTRODUCTION

In January 1994, representatives of the Division of Physics of Beams (DPB) of the American Physical Society (APS) approached Dr. Martha Krebs, Director of the Department of Energy (DOE) Office of Energy Research (OER), to propose that a study be done on the importance of accelerator physics and technology to the nation. After taking the proposal under advisement, Dr. Krebs decided to initiate an examination of accelerator science and technology as supported by five OER programs: High Energy Physics (HEP), Nuclear Physics (NP), Basic Energy Sciences (BES), Fusion Energy (OFE), and Health and Environmental Research (OHER). Dr. Krebs asked the High Energy Physics Advisory Panel (HEPAP) to assume executive responsibility for establishing a composite subpanel with representation from all five OER program advisory committees (HEPAP, Nuclear Science Advisory Committee [NSAC], Basic Energy Sciences Advisory Committee [BESAC], Fusion Energy Advisory Committee [FEAC], and Health and Environmental Research Advisory Committee [HERAC]) to perform the study, and she conveyed to the chairman of HEPAP a Charge to the Subpanel (Appendix A).

In her charge, Dr. Krebs requested that the composite subpanel carry out a broad assessment of the current status and promise of the field of accelerator physics and technology with respect to the five OER programs and provide recommendations and guidance to her on appropriate future research and development needs, management issues, and funding requirements. The Subpanel was given wide latitude in carrying out the study, but the following issues and questions were to be addressed:

- A. Review and summarize the role that accelerators, storage rings and colliding beam devices play in the OER research programs, providing also a brief summary of the R&D carried out within each program to support accelerator, storage ring, and colliding beam facility operations; for the

improvement of existing facilities; and for the development of new facilities.

- B. Provide an assessment of spin-offs and applications from the OER accelerator R&D activities with a focus on contributions to the productivity and competitiveness of American science, industry, and medicine in a world economy.
- C. Determine if the level of R&D for each OER program is appropriate, in terms of R&D content, activity level, and funding, to ensure the success of the scientific goals of that program and to assess future opportunities to meet national needs through accelerator science.
- D. Examine the approach used by the five individual OER program offices in managing their R&D activities in accelerator physics and technology to determine if each is appropriate to the overall needs of that program.

In response to Dr. Krebs' request, this Composite Subpanel for the Assessment of the Status of Accelerator Physics and Technology was set up with five members who also served as liaison representatives for each of the five advisory committees that advise OER. The balance of membership was drawn from both the accelerator community and from those scientific disciplines associated with the OER programs. Appendix B provides the full Subpanel membership.

An early response of the Subpanel to the charge was a decision to seek information and advice using an open and participatory process. Three meetings were held to gather information from OER program managers, accelerator physicists, and scientists representing the major scientific fields enabled by accelerators. The information addressed the long-range directions and needs of the OER programs and the scope, funding, and management of accelerator R&D within OER. The first

meeting, on June 28-29, 1995, included presentations by representatives of the five OER programs. It also included a session with Dr. Krebs on her expectations of the Subpanel. The second meeting was held August 2-3, 1995. Information was provided by members of the accelerator community whose names had been suggested by the executive committee of the APS DPB. Representatives from DOE's Defense Programs (DP) and the National Science Foundation (NSF) also spoke to the Subpanel. An "open mike" session provided opportunity for anyone to speak. The third meeting was held September 8-10, 1995, and consisted of input from sixteen eminent and visionary scientists selected by the five OER advisory committees as representative of the relevant scientific communities. Throughout the meetings, designated representatives of the five OER programs were invited to be present as observers and participants.

Appendix C provides the agendas for all three information-gathering meetings, including names and affiliations of those providing testimony to the Subpanel. The Subpanel also gathered information on accelerator R&D efforts from the national laboratories, university facilities supported by DOE and NSF, and DOE program managers. An acknowledgment of other sources of information is also provided in Appendix C.

This wealth of information provided the Subpanel with a broad perspective regarding the status of accelerator science and technology, the scope of current accelerator R&D, and future directions of scientific fields that use accelerator-based technology in support of the OER mission.

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II. DEPARTMENT OF ENERGY OFFICE OF ENERGY RESEARCH STEWARDSHIP RESPONSIBILITIES FOR ACCELERATOR SCIENCE AND TECHNOLOGY

Over the past 50 years or more, accelerator science and technology has provided essential capabilities for the Department of Energy Office of Energy Research (DOE/OER) research programs. It has had an enormous impact on the nation's scientific research and has significantly enhanced the nation's biomedical and industrial capabilities. Much of this impact can be traced to the support of forefront accelerator research and development as part of the DOE/OER programs and to the support of such activities by the DOE's predecessor agencies, the Atomic Energy Commission (AEC) and the Energy Research and Development Agency (ERDA). It is the view of this Subpanel that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have held a *de facto* national trust for the stewardship of accelerator science and accelerator-based technology development. This stewardship has provided the foundation for essential capabilities needed both for the DOE mission and for addressing broader national interests.

Although many significant contributions to the accelerator field have been made by researchers supported by other government entities and by other nations, it is the high level of investment in accelerator science and technology by the AEC, ERDA, and DOE, the sustained level of commitment, and the number and impact of the developments resulting from this support that leads the Subpanel to this point of view. Appendices D and E document many of these contributions that have flowed from the investments made by AEC, ERDA, and DOE in the accelerator field over the past half century.

This Subpanel's recognition of the importance of DOE/OER's historical stewardship role emerged from hearing and considering detailed information from the DOE/OER program offices, from other parts of the agency, from the accelerator

science community, and especially from a panel of highly regarded researchers whose collective vision spans the full range of the OER mission.

The Subpanel strongly believes that it is vital that the DOE and its OER programs continue to hold accelerator science and technology as a national trust. This trust and the resulting stewardship responsibilities should now be an explicit rather than a de facto part of the overall DOE/OER mission to ensure that this activity will be effectively and consistently pursued. These stewardship responsibilities are essential if accelerator science and technology are to continue to support the DOE mission and the national interest.

This Subpanel has considered the range and depth of stewardship responsibilities that should be an explicit part of OER's portfolio and mission. In the Subpanel's view, the following are the important stewardship responsibilities:

- A. Design, construction, and improvement of accelerator-based facilities providing vital capabilities needed to carry out the mission of DOE's OER programs.
- B. Effective utilization and operation of these accelerator-based facilities.
- C. Support of the accelerator R&D required to provide facilities at the technological cutting-edge for the sciences that they serve.
- D. Appropriate investment in basic accelerator science and related technology R&D to form the foundation for capabilities needed in the future.
- E. Support of the training of the accelerator scientists and engineers required to provide the accelerator-based capabilities needed in future years.

- F. Support for the continued development and maintenance of the basic tools needed to stay at the cutting edge in the accelerator field (e.g., computer codes, essential stand-alone test facilities, and critical infrastructure elements at the accelerator-based facilities).

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III. CONTRIBUTIONS TO OFFICE OF ENERGY RESEARCH SCIENTIFIC MISSIONS

The Office of Energy Research (OER) provided approximately \$1.7B of support for basic research in FY1995. If the additional investment in instrumentation and the construction of major research facilities is included, OER ranks second only to the National Institutes of Health (NIH) in research investment. As stated in the OER Strategic Plan (DOE/ER-0656), OER supports “programs of basic and applied research that support the Department's energy, environmental, and national defense missions and that provide the foundation for technical advancement.” The range of scientific fields supported by OER is consequently extensive, including: material and chemical sciences, geosciences, engineering, energy biosciences, fusion, high energy and nuclear physics, nuclear medical applications, environmental studies, and general life sciences, including the Human Genome Project. The research facilities and infrastructure developed and supported through OER enable key components of research in these many fields for thousands of researchers funded by the Department, other agencies, and industry.

In this section, we briefly summarize the extent and manner by which accelerator physics and technology play a critical role in making it possible for the United States to push forward the frontiers of research in this extensive array of scientific fields. More detailed descriptions of the scientific programs and the role played by accelerators in each of the five OER programs are given in Appendix D.

High Energy Physics

High energy physics studies the fundamental structure of matter and the laws governing the interactions of the basic constituents of the Universe. During the last decades, experiments on accelerators and colliders have enabled high energy physicists to develop a deep understanding of the basic constituents of matter and their interactions. As the energy and the intensity of accelerators and colliders increased,

new subatomic particles were discovered, and their interaction elucidated. Thus, the progress in high energy physics has been strictly paced by the progress in the physics and technology of accelerators, establishing a tight correlation between the two disciplines.

Major high energy physics accomplishments at U.S. accelerators during the past 25 years include:

- The discovery of the τ -lepton, and the charm, bottom, and top quarks. These discoveries led directly to the Standard Model of quarks and leptons that is the synthesis of the current understanding of fundamental particles and their interactions.
- Systematic studies of the properties of these new particles including measurements of masses and decay ratios. Much of our knowledge of the strong and electroweak forces comes from the results of these experiments.
- Experiments probing the structure of protons and neutrons, the particles that make up nuclei.
- Experiments that search for physics beyond the Standard Model. These include searches for rare or forbidden decays of elementary particles, and precision measurements of decay ratios, scattering probabilities, and beam polarization dependence.

High energy physics experiments are presently being done at Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC), Brookhaven National Laboratory (BNL), and Cornell in the United States, and also at laboratories in Europe, Japan, China, and Russia. The U.S. program is centered on fixed-target experiments at BNL (high-intensity proton beams accelerated to 30 GeV),

Fermilab (protons accelerated to 800 GeV), and SLAC (electrons accelerated to 50 GeV), and collider experiments at Fermilab (proton and antiproton beams accelerated up to 900 GeV per beam), SLAC (electron and positron beams accelerated up to 50 GeV per beam) and Cornell (electron and positron beams accelerated up to 6 GeV per beam). The Fermilab Tevatron collider is presently the highest energy collider in the world. The Stanford Linear Collider (SLC) at SLAC is the world's first linear collider. The Cornell Electron Storage Ring (CESR) at Cornell is the world's highest luminosity electron-positron collider. After the cancellation of the Superconducting Super Collider (SSC), the U.S. high energy physics community participation in the Large Hadron Collider (LHC) program at the European Laboratory for Particle Physics (CERN) has become a high priority.

Measuring top quark properties, exploring the particle-antiparticle asymmetry in nature, and elucidating the Higgs mechanism, the means by which particles obtain mass, are some of the most exciting scientific challenges for this field today. As in the past, progress on these scientific issues requires advances in the physics and technology of accelerators. The Fermilab Main Injector project will increase the Tevatron luminosity and the top quark production rate substantially. B-meson decay probes the particle-antiparticle asymmetry, and Positron-Electron Project (PEPII) (the SLAC asymmetric B-Factory now under construction) and the CESR luminosity upgrade are aimed at significant B-meson production rates.

Study of the Higgs mechanism requires higher energy than now available, and colliders with higher energy and luminosity are being designed and studied to further expand the high energy physics frontier. The LHC at CERN is a European project in which U.S. participation is being negotiated at the time this report is being written. The design of a next-generation, high-energy linear collider has advanced to a stage that includes engineering and cost considerations as well as prototypes and studies of underlying accelerator physics. Much of this work is being done in a large international collaboration involving the United States, Europe, and Japan. Other ideas

for future colliders are being studied although the work is not now as developed as that for a future linear collider. These ideas include: photon-photon colliders, TeV lepton colliders using unstable muons, and high-luminosity, multi-TeV proton colliders. Novel accelerator concepts, such as plasma-based acceleration in non-conventional structures, are being studied with the goal of further reductions in accelerator cost and size.

Nuclear Physics

The goal of nuclear physics research is to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior. Nuclear physics research depends, to a large degree, on the use of accelerators for its experimental investigation. Corresponding to the diversity of the field, a relatively large number of accelerator facilities of varying energy, type, and particle beams are employed. While early experiments were most frequently conducted at university-based small accelerators, the steadily increasing requirements in energy, intensity, and beam species have led to large, dedicated nuclear physics accelerator facilities.

Major nuclear physics accomplishments at U.S. accelerators during the past 25 years include:

- The exploration of the single-particle and the collective degrees of freedom and of the underlying symmetries in the strong-interaction nuclear many-body system.
- The rather complete description of the strong nucleon-nucleon interaction and its application to nuclei.

- The discovery of the parton structure of nuclei.
- The discovery of numerous new chemical elements up to element 111.
- The generation of hot, dense nuclear matter in the laboratory, allowing the study of hadronic matter under conditions approaching those present in neutron stars and at the origin of the universe.
- The study of nuclear reactions involving nuclei far from stability, which provide direct experimental information on important astrophysical processes, including those that fuel the Sun and determine nucleosynthesis.
- Precision measurements of the properties of the neutrino and the weak interaction, which help shape the Standard Model of fundamental particles and interactions.
- Development of accelerator mass spectrometry, the ultrasensitive detection method for long-lived radioisotopes, which has revolutionized archeological dating and found widespread application in various other areas of interdisciplinary research.

The present scientific objectives in nuclear physics can be grouped into four broad thrusts outlined in the 1996 Nuclear Science Advisory Committee Long-Range Plan.

The first objective is to explore the limits of nuclear structure and dynamics. In this area, nuclei are studied at the extremes of spin, temperature, and isospin, and in regions near the drip lines where nuclear binding comes to an end. An illustrative example is the study of the structures and symmetries governing the behavior of rapidly rotating, highly deformed nuclei. Most experiments in this field are performed

at smaller facilities that have been developed at both national laboratories and universities to provide unique capabilities in terms of beam species and characteristics.

The second broad thrust in nuclear physics is directed at the quark structure of matter. Here the field strives to understand nuclei and nuclear forces in terms of quantum chromodynamics (QCD), that is, the interactions of the underlying fundamental constituents, quarks and gluons, and to establish a bridge from this new understanding to descriptions in terms of nucleons and mesons. Beams of electrons, photons, and protons are essential tools. A major new facility, the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia, is aimed at this area of nuclear physics research.

Strongly interacting nuclear matter is expected to undergo phase transitions when exposed to extreme conditions. This defines a third major thrust of nuclear physics research, which attempts, through heavy-ion collisions at intermediate and very high energies, to explore the equivalent of a liquid-gas phase transition for quantum systems and the transition from hot, dense nuclear matter to a quark-gluon plasma. Producing this latter state of matter, in which quarks and gluons are deconfined, will be the objective of research at the Relativistic Heavy Ion Collider (RHIC), now under construction at BNL. At present, the heavy ion physics program at Brookhaven utilizes the AGS for fixed-target experiments aimed at exploration of nuclear matter under extreme conditions.

The fourth objective concerns fundamental symmetries and tests of the Standard Model at low energies, and their connection to nuclear astrophysics. Precision experiments (focusing, for example, on parity violation) with the techniques of nuclear physics (for example, electron scattering of nucleons and nuclei) can shed light on the limitations of the Standard Model in ways complementary to high energy physics. A major component in this area of research is the study of neutrino properties, involving both accelerators and non-accelerator facilities.

CEBAF and RHIC are currently the major investments of nuclear physics in forefront accelerator facilities. In the long term, their operation and the research efforts of their university-based users, will occupy more than half of the planned Department of Energy (DOE) nuclear physics budget.

A number of smaller accelerator facilities at universities and national laboratories around the country have unique characteristics and capabilities. These facilities are supported by both DOE and the National Science Foundation (NSF) and provide training for graduate students in a direct, hands-on manner. They constitute an important component in the nuclear physics program. Brief descriptions of the nuclear physics facilities are given in Appendix D.

Some nuclear physics research also utilizes high energy physics accelerator facilities, such as the program at the Alternating Gradient Synchrotron (AGS) at BNL, which uses both heavy-ion and proton beams in a fixed-target mode. Other experiments are being carried out at Fermilab and at Deutsches Elektronen Synchrotron (DESY) in Germany.

With the operation of CEBAF, the completion of RHIC, and new radioactive beam facilities, accelerators and accelerator technology developments are defining many of the forefront opportunities in nuclear physics research.

Basic Energy Sciences

The mission of Basic Energy Sciences (BES) is to expand scientific knowledge and technical skills needed to aid long-term economic growth and to develop new and existing energy resources. BES has sub-programs in materials science, chemical science, biosciences, and earth sciences. A component of the research performed for the BES materials science and chemical science programs is done at a suite of major accelerator-based facilities operated by BES—four of the nation's eight synchrotron

light sources (the Advanced Light Source [ALS] at Lawrence Berkeley National Laboratory [LBNL], the Advanced Photon Source [APS] at Argonne National Laboratory [ANL], the National Synchrotron Light Source [NSLS] at BNL, and Stanford Synchrotron Radiation Laboratory [SSRL] at SLAC) and the two U.S. pulsed neutron sources (the Intense Pulsed Neutron Source [IPNS] at ANL and Los Alamos Neutron Scattering Center [LANSCE] at Los Alamos National Laboratory [LANL]). At present, no additional light sources or neutron sources are under construction. However, beam lines are being added at existing light sources, and a design study is underway for a state-of-the-art pulsed spallation neutron source. BES also supports programs at national laboratories and universities using electron microscopes and ion-implantation facilities for characterization and modification of a wide variety of materials. All of these BES-supported accelerated-based research facilities are used by thousands of basic and applied scientists supported by the DOE, other Government agencies, and industry (see Appendix D).

Neutron Scattering. Neutron sources have provided capabilities which have led to important advances in basic science and technology. The following are some examples:

- Ever since the discovery of the high-T_c ceramics, neutrons have been the principal contributors to the knowledge of their structures because of the sensitivity of neutrons to light atoms (here, importantly, oxygen) in the presence of heavy ones.
- Chopper spectrometers at pulsed neutron sources have made possible measurements of the Bose condensate fraction in superfluid helium.
- Neutrons have thrown new light on the conformations and interactions of polymeric materials in bulk and solution. Using proton/deuteron substitution, individual molecules or segments of molecules can be labeled.

- Because neutrons penetrate centimeter depths in many materials, high resolution neutron diffraction can probe the strain distribution in bulk materials. Measurements of residual stresses in welded sections and plastically deformed specimens, and temperature dependence of stresses in fiber-reinforced composites provide the basis for new understanding of engineering materials.
- Neutron radiography finds many technical applications, such as in the inspection of aircraft structures for evidence of corrosion and in the radiography of turbine blades.
- The recently-developed technique of neutron reflectometry provides a way to determine the variation of chemical composition and (using polarized neutrons) the magnetization density in films, multilayers, and bulk material surfaces.

Increases in neutron flux, such as would be provided by next-generation spallation neutron sources, would lead directly to increased capability for these and other studies.

Synchrotron Radiation. The increasing availability and capability of synchrotron radiation has provided major benefits to many fields of research relating to BES programs—including chemistry, materials science, and surface science—as well as to technology. Examples include:

- High-resolution, angle-resolved photoemission experiments have generated new understanding of highly correlated and magnetic materials, including high temperature superconductors.
- In-situ studies of organometallic vapor phase epitaxial growth using X-ray diffraction have contributed vital information on this technique, which is

used commercially to produce high quality GaAs, CdTe and other important semiconductors.

- Nondestructive measurement of silicon wafer cleanliness with linearly polarized synchrotron radiation has achieved about a factor of 20 improvement in the detection limits with a technique called total reflection X-ray fluorescence. Such improvements in sensitivity will be critical to the development of the next generation of integrated circuits.
- Circularly polarized soft X-rays have been used to study magnetic materials, including the magnetic and magneto-optic recording materials that underlie data storage in the computer industry. X-rays avoid the diffraction limit of laser light and can penetrate coatings to image the shape and properties of magnetic recording bits.
- The high brightness and tunability of synchrotron radiation from the IR to hard X-rays has led to major advances in spectromicroscopy. A variety of chemically selective imaging techniques are used, including scanning transmission and photoelectron imaging, to study many different materials, ranging from semiconductors to radioactive materials to materials of forensic interest.
- The selective ionization made possible by tunable synchrotron radiation has been used, together with lasers and molecular beams, to study processes relating to combustion and photochemistry in general, including the dynamics of ozone dissociation in the atmosphere.

The performance of synchrotron radiation light sources has increased greatly with advances in accelerators and insertion-device technology. For example, X-ray source brightness has increased by about 11 orders of magnitude during the past 25

years. Since we are still far from fundamental limits on source performance, ideas for next-generation light sources are now being developed. These include storage rings with lower electron beam emittance and short wavelength free electron lasers (FELs). The latter would offer X-ray beams with full transverse coherence and with a peak brightness about 10 orders of magnitude higher than that available today.

Health and Environmental Research

The Office of Health and Environmental Research (OHER) develops and supports fundamental science that underpins the strategic goals of the DOE in areas related to health and environmental effects. The program mission is to "develop the knowledge needed to identify, understand, and anticipate the long-term health and environmental consequences of energy production, development, and use."

Accelerator-based technologies contribute to several OHER strategic objectives: using unique national laboratory facilities for structural studies at the molecular and cellular level, developing advanced medical technologies and radiopharmaceuticals, and contributing to environmental cleanup by developing advanced remediation tools.

Operations and direct support of accelerator facilities are not part of the direct mission orientation of OHER, nor is R&D on them. Some accelerator operations are supported as part of research programs on isotope production at accelerators. The Office does support R&D at accelerator-based *user* facilities in areas relevant to achieving the above strategic objectives. In some of these cases, OHER cooperates closely with other Offices such as BES or other Federal agencies (NIH and NSF) to achieve its goals most effectively and to best meet the needs of the national scientific user community.

A particularly important example is OHER's program to enable the effective use of synchrotron radiation for structural molecular biology research. Structural molecular biologists use information on biological structure at atomic resolution to

gain fundamental insights into function (such as muscle contraction), into biological processes (like cell division and cancer), and to provide the means to design new drugs to correct malfunction or disease (like viral and bacterial infections). During the past decade synchrotron radiation has become recognized as an extremely powerful tool enabling state-of-the-art research in this area, leading to a rapidly growing user community and a need for more beam time.

In the environmental area, synchrotron radiation studies of the electronic structure and speciation of actinides in weapons plant waste products provides vital information relevant to developing strategies for remediation and long-term storage.

National user facilities developed and supported by OHER at the synchrotron facilities operated by BES are the primary means by which OHER program needs are being met. OHER supports R&D activities on the development of new beam lines, insertion devices (wigglers and undulators), and optical systems tailored to produce radiation optimized for the study of biological and environmental samples. Other areas to which OHER provides support include the development of: specialized sample manipulation instrumentation, advanced detectors for both synchrotron and neutron applications, and advanced computational methodologies.

In nuclear medicine, OHER supports the development of new target designs for the efficient production of radioisotopes at accelerators, with current emphasis on modeling of heat transfer properties to permit the handling of deposited beam power. The program also funds identification and development of procedures for production at accelerators of new isotopes for medical research, including nuclear cross-section studies, targetry research, development of radioanalytical methodologies, and neutron therapy for brain tumors.

Fusion Energy

Fusion is the process that powers the Sun and the stars. The oceans and other waters contain vast quantities of the fuel needed to power fusion reactions, and the goal of fusion energy research is the production of controlled fusion energy for electric power generation. This is a daunting goal. Worldwide, the total continuing investment for fusion research is approximately \$1B per year. After more than 40 years of research, fusion devices have only recently begun producing megawatts of power, and commercialization will still require several decades of research.

There are two principal approaches to fusion energy, magnetic and inertial, and OER supports research on both. In addition, DOE's Office of Defense Programs (DP) supports the Inertial Confinement Fusion Program for defense applications.

Accelerators play three principal roles and several subsidiary roles in the OER fusion program. The principal roles are discussed below.

Plasma heating for magnetic fusion energy. The neutral-beam accelerators for plasma heating recently enabled the Tokamak Fusion Test Reactor (TFTR) at Princeton to achieve a world-record fusion power level of approximately 10 MW.

Drivers for inertial fusion energy. Accelerator drivers for inertial fusion have demanding requirements on beam current and beam brightness. While some of the accelerator technology has already been developed by other OER programs, the study of these requirements has been an important factor in the creation of a new subfield of accelerator science, the physics of high-current beams. The combination of research into high-current beams with research into target physics supported by DOE/DP makes inertial fusion energy potentially a cost-effective development path to a commercial power plant. In addition to fusion, high currents are essential for many of the other new applications of accelerator technology such as destruction of radioactive waste, isotope production, food treatment, energy production, and defense.

Materials testing. The ultimate attractiveness of magnetic fusion energy depends on the development of low-activation materials that behave well under irradiation by neutrons. The Rotating Target Neutron Source accelerator has already provided important information regarding the behavior of materials, including optical materials, under neutron irradiation. The Fusion Energy Advisory Committee has concluded that it will be necessary to build a new, high-fluence neutron source for magnetic fusion energy materials development to continue these studies in the future and that an accelerator-based source is the system of choice.

Each of these roles could be critically important to fusion research, but support has not been steady. This is discussed in more detail in Appendix D.

IV. CONTRIBUTIONS TO THE NATION

Maintaining our nation's premier status in accelerator science and technology is necessary not only for the Office of Energy Research (OER) to fulfill its mission but also to provide broader benefits to the overall national interest such as keeping our economy vital through contributions to industrial innovation and advancement of medical and other applications. Many technologies that have evolved directly from developments in accelerator science over roughly the past 50 years have found significant applications in arenas of importance to the nation. A number of these applications, including medicine and health care, energy, and the environment, overlap the mission of the U.S. Department of Energy (DOE), while many others, such as industrial processing, directly benefit society at large. The DOE can be proud of the technical applications that benefit society and enhance U.S. competitiveness in the world market. In this section, we highlight the wide range of beneficial contributions that stem from accelerator concepts and discuss the mechanisms by which DOE technical achievements are spun off to industry (Appendix E provides a more complete description of these benefits).

Major Benefits to the Nation

There are well established applications of accelerator science and technology in diagnostic and therapeutic medicine for research and routine clinical treatments. A significant fraction of the radioisotopes used in treatment, diagnostics, and research are produced by accelerators. Beams of X-rays, neutrons, protons, and ions that are derived from particle accelerators are currently used in the treatment of cancer and other disease, while accelerators are used in many biomedical research programs to explore both beam-related treatment modalities and to develop other approaches to therapy. An example of the latter is the use of synchrotron radiation sources and high-

resolution X-ray crystallography to characterize the structure of viruses. If the link between structure and function can be determined, it may be possible to develop designer drugs that can subtly alter the viral structure so as to interfere with its functional ability to cause disease. Researchers are also using accelerator-based X-ray sources to develop approaches to non-invasive angiography in hopes of significantly reducing the risks associated with this important diagnostic tool.

Accelerators and associated technologies have various important uses in industry for R&D, manufacturing, testing, and process control. Industrial researchers, in common with materials scientists in universities and national laboratories, use synchrotron radiation, neutron scattering, and other accelerator-based techniques as important tools in their R&D activities. In industry, the R&D is often undertaken to develop new products—for example, high-density magnetic storage media. In manufacturing, beams from accelerators are used to alter material composition (e.g., ion implantation); to improve important characteristics of a product (e.g., sterilization of medical equipment and the hardening of surfaces for greater wear resistance); as a basic part of the production process (e.g., ion implantation and X-ray lithography in silicon wafer production, or X-ray micromachining); to improve industrial processes (e.g., curing epoxies and plastics); and to provide information about manufacturing processes (e.g., wear studies of materials or characterization of impurities in semiconductors).

Accelerator systems are important tools in fundamental and applied research. In addition to those uses mentioned elsewhere in this report, accelerators are used for accurate, nondestructive dating of archeological samples and art objects, and by National Aeronautics and Space Administration (NASA) for simulation of cosmic rays to determine the impact of this radiation on astronauts. Electron microscopes use electron beams to provide the detailed

images that permit researchers to understand the structure of biological and other materials. Developments in the understanding of beam dynamics and control hold promise for advancing electron microscopy capabilities.

Accelerators hold promise for impacting a number of critical societal problems, including energy production, waste treatment, and defense applications. Accelerators are a significant part of the fusion energy program and could be used to burn radioactive waste while generating useful energy. Food sterilization with beams could have significant benefits for food storage and distribution. Though still in its infancy, an accelerator-based, antiballistic missile system continues to be pursued. Finally, the use of accelerators to produce tritium for thermonuclear weaponry is now being considered as a leading approach in the coming decade.

These and other benefits are discussed in greater detail in Appendix E.

Interaction with the Private Sector

In this section, we briefly describe two Federal programs that involve accelerator R&D and provide economic benefit to the private sector. These are the Small Business Innovation Research (SBIR) program and the Cooperative Research and Development Agreement (CRADA) program.

By law, every Government agency that funds more than \$100M in extramural R&D must set aside a percentage of its R&D funds (2% in FY1996) to conduct an SBIR program. Small businesses submit research proposals and compete for awards once a year. Awardees receive up to \$75K in Phase I, then within a year compete for Phase II awards, which provide up to a total of \$750K for two years.

In the DOE, SBIR proposals are thoroughly peer-reviewed and the award process is quite competitive. SBIR proposals can only be submitted for specified research topics chosen by DOE programs. The current list of 41 topics includes several with direct relevance to accelerator physics, including *Technology and Instrumentation for High Energy Accelerators*, *Nuclear Physics Accelerator Technology*, and *Technology and Instrumentation for Heavy Ion Fusion Accelerators*. Other topics such as *Medical Applications* and *Fusion Energy Systems* frequently involve some degree of accelerator R&D. There are additional technical topics on instrumentation, data processing, and detector technology of interest to OER scientific programs. Award decisions are made by a combination of SBIR managers and appropriate DOE program office technical managers, after proposal review.

Examples of past successful projects include advances in superconducting wire and cable fabrication, development of new radiofrequency sources, target development for isotope production, and numerous improvements in electronic instrumentation. The SBIR program provides a significant source of additional funds for accelerator R&D, supporting OER scientific and technical goals as well as technology transfer to industry. Current Phase I SBIR programs include:

- Development and fabrication of superconducting wire (six projects)
- Advanced microwave concepts (seven projects)
- Electronic instrumentation, data acquisition, control, and new detectors (seven projects)
- Other projects involving innovative solutions to specific problems and needs (seven projects).

In contrast to SBIRs, CRADAs require a negotiated agreement between a laboratory and a commercial entity. They began as a result of Federal legislation passed during the 1980s to assist in commercializing spinoffs so that society can benefit from the extensive funds invested in science and technology.

Generally, collaboration between laboratories and the private sector for technology transfer has had mixed success because: (1) rigid procedural requirements, including intellectual property issues, make cooperative research between the labs and the private sector difficult; and (2) organizational cultures differ in perspectives and value systems, especially with regard to views on cost, schedules, the concept of deliverables, and optimization strategies for generic technology development.

Within the last year, three important studies involving the role of Federal research in fostering economic vigor and competitiveness have been completed:

- *Alternative Futures for the Department of Energy National Laboratories* (the so-called Galvin Committee Report), DOE, February 1995
- *Energy R&D: Shaping Our Nation's Future in a Competitive World* (the so-called Yergin Panel Report), DOE, June 1995
- *Allocating Federal Funds for Science and Technology*, National Academy of Sciences, December 1995.

All three reports recognize that there is only a limited role for Federal science to contribute to industry; however, they also recognize that private sector R&D is concentrating on shorter and shorter time horizons. Thus, Federal research

facilities can make a contribution if the particular technology is closely related to a core mission of the laboratory and if it is not something that industry would fund on its own anyway. The last two reports acknowledge that there are areas in which the national interest is not served by the market alone, such as new enabling or broadly applicable technologies.

In analyzing industry-laboratory interaction, the Subpanel has reached the following conclusions. First, some (perhaps many) national laboratory R&D activities are not relevant to industrial technology commercialization. Second, the highest probability of successful technology transfer occurs when there is user (industry) pull, as opposed to technology push from the laboratories, i.e., a perceived need should be the focus for identifying a commercialization opportunity. Third, the critical interface necessary for successful transfer and adoption of the technology involved is people-to-people contact. With these findings in mind, we offer the following suggestions for improving the impact of accelerator technology on society.

A. Laboratory technologies should be better publicized to industry.

Experience with the Fermilab Industrial Affiliates Association and similar organizations elsewhere indicates that industry will make an effort to understand the technologies.

B. Protocols for laboratory-industry interaction should be designed to minimize administrative and funding delays in the execution of cooperative projects.

C. Laboratory managers should increase emphasis on the transition of laboratory technologies to the private sector and encourage scientists and engineers in their organizations to assist in transferring technology.

These issues must be addressed if DOE is to become more effective in contributing to U.S. competitiveness. In addition, the Subpanel believes that more attention should be paid within the DOE to providing an environment in which emerging technologies that do not fit into mainstream programs can be nurtured and possibly develop into new mainstream programs or into spinoffs.

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V. ACCELERATOR SCIENCE AND TECHNOLOGY

Advances in accelerator physics and technology have driven fundamental scientific research programs and led to significant societal impact during roughly the past 50 years. The field of accelerators began as an appendage to the fledgling fields of high energy physics (HEP) and nuclear physics (NP), providing these fields with essential experimental tools. Over the years, accelerator physics has matured into a scientific field in its own right. This new status is evidenced by sophisticated mathematical and computational tools for modeling beam behavior, experimental programs to study the basic physics of beams and the technology for producing beams, and journals and graduate level degree programs dedicated to accelerator physics. The American Physical Society (APS) has acknowledged the scientific status of the field by creating a Division of Physics of Beams (DPB).

The invention of the cyclotron in 1930 can be viewed as the start of the field of accelerator physics. This was followed by the discovery of phase stability and the invention of alternating-gradient focusing. These and other advances in accelerator technology have led to a million-fold increase in particle beam energy. We are now at the point where R&D on accelerator science leads in the medium-term to the construction of facilities and to facility upgrades that greatly expand the potential for scientific research. At the same time, long-term accelerator R&D is likely to make possible new capabilities that will benefit an ever-wider realm of science.

Accelerator physics and technology as a scientific discipline is practiced in universities as well as at the national laboratories, thus accessing the talent of university researchers and providing a training ground for students, who will become the next generation of scholars in this field and will also contribute to other scientific and technological fields.

Each Office of Energy Research (OER) program uses accelerators to a different extent. Appendix F details the frontiers of accelerator science and technology and the potential advances of further medium and long-term R&D in each program. These frontiers and potential advances indicate that specific long-term R&D is likely to have an impact in more than one OER program. For example, production and acceleration of high brightness electron beams will help both HEP, through the development of future linear colliders, and Basic Energy Sciences (BES), through increased brightness photon beams and free electron lasers (FELs). This translates into extension of our knowledge of the subatomic world and new tools for materials and biological research. Continued R&D on superconducting rf structures and the use of new superconducting materials can lead to improved accelerator capabilities for high energy and nuclear physics as well as for advanced FEL drivers. In addition, particle beams are one of the best tools for studying nonlinear physics. This field has applications all the way from celestial mechanics to biology and chaos theory. Finally, R&D on the production and transport of high intensity ion beams will make important contributions in HEP, NP, Fusion, BES, and other U.S. Department of Energy (DOE) programs outside OER, such as radioactive waste processing and tritium production. Other examples of such beneficial accelerator research can be found in Appendix F and include:

- beam stability and feedback
- storage ring quality magnets
- new superconducting materials
- novel lattices and beam optics
- high efficiency rf sources and accelerating structures
- beam polarization
- beam cooling
- targeting
- beam instrumentation and diagnostics

- beam control
- particle sources
- computer codes

It is important to recognize that unless the basic scientific knowledge is created to extend the reach of these generic areas, the field of accelerators will not continue to be as fruitful as it has been in the past in giving new tools to the DOE and to the nation to accomplish new goals. Unless new basic research is done, the old boundaries will restrict us to old levels of accomplishment.

Short, medium, and long-term accelerator R&D activities in individual OER programs were reviewed by the Subpanel (see Appendix F). Strong short-term and medium-term R&D programs exist at major accelerator facilities. To a lesser extent, long-term R&D programs are supported at some facilities. Only HEP has a major proposal-driven peer-reviewed program that supports medium and long-term R&D at universities and DOE facilities. This program has been successful with important contributions to superconducting wire development, to accelerator theory, to high-gradient acceleration, and to the support of accelerator education.

A strengthened long-term R&D program will have significant positive impact with regard to future facilities and the potential for scientific research in all OER programs.

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VI. MANAGEMENT AND FUNDING

The Subpanel examined the approach used by five Office of Energy Research (OER) programs in managing and funding their R&D activities in accelerator physics and technology to determine if each is appropriate to the overall needs of that program. A summary of that analysis and the conclusions drawn from it are presented in this section.

Management Approaches of Five Office of Energy Research Programs

The Subpanel identified three broad categories of accelerator research and development that are pertinent to accelerator-related activities supported by OER programs. Although these R&D categories sometimes overlap, they provide useful distinctions for commenting on the management of accelerator R&D activities by the five OER program offices.

- *Short-term R&D* is focused on the design, construction, operation, and improvement of existing or approved facilities. Such R&D is generally conducted at a national laboratory or accelerator facility where management determines the scope of this R&D.
- *Medium-term R&D* is related to future capabilities of interest to a specific laboratory or facility. Such R&D is most frequently conducted at a national laboratory or accelerator facility where management determines the scope of this R&D.
- *Long-term R&D* provides the scientific basis for the enabling concepts and technologies that drive the development of important future accelerator-based capabilities. It furthers the fundamental understanding of accelerators and maintains the vitality of

accelerator science as a science. As such, it is the basic research component of accelerator R&D. Examples of high impact past activities of this type are the successful development of superconducting rf cavities, high-current superconducting wire, and laser-driven, low-emittance photocathode electron sources. Long-term R&D involves the broader intellectual base available in the universities and the accelerator community.

The Office of Health and Environmental Research (OHER) funds specialized facilities for biological and environmental research at accelerators constructed and operated by Basic Energy Sciences (BES). OHER policy is that accelerator operations and R&D are not part of its direct mission, and it does not support accelerator R&D of any type above. It does support R&D in areas that directly enhance accelerator utilization, such as beamlines, instrumentation, and support facilities. OHER and closely related National Institutes of Health (NIH) activities are one of the growth areas in synchrotron radiation based sciences, and the presentations the Subpanel heard from OHER users were among the most demanding and the most creative in terms of future accelerator capabilities.

The OHER policy means that accelerator R&D needed for operational improvements and to pursue future directions will not be performed unless there is overlap with the interests of other OER programs and the relevant R&D is initiated and funded by those programs. For short-term and possibly medium-term R&D there is a substantial shared interest between OHER and BES. For long-term R&D (and for some medium-term research) there may or may not be such overlap with other OER programs. When there is overlap in these needed developments, they will be pursued with the schedule and priority of the other OER program rather than those of OHER. When there is no

overlap, there is some risk that accelerator capabilities needed for future OHER research will be unavailable.

Basic Energy Sciences (BES), High Energy Physics (HEP), and Nuclear Physics (NP) operate accelerators for scientists supported by these programs, by related programs such as OHER at BES facilities, and by other Federal agencies, including the National Science Foundation (NSF) and the NIH. They have a common approach to short-term accelerator R&D. The accelerator program is managed by the facility using resources provided to it by the DOE. The priority of a particular activity within the accelerator program itself and within the broader program of the facility is determined by the facility managers working within their budget constraints. The overall scientific program of the facility is reviewed by laboratory visiting committees, by DOE committees, or both, and the accelerator activities are reviewed primarily in the context of that overall program.

These three programs manage medium-term accelerator R&D with somewhat different emphasis. In BES and NP, facility managers can and do devote resources provided to the facility for development of future capabilities. Current examples include free electron laser (FEL) development for BES at the National Synchrotron Light Source (NSLS) and the Stanford Synchrotron Radiation Laboratory (SSRL) and radioactive beams for nuclear physics at Lawrence Berkeley National Laboratory (LBNL), Argonne National Laboratory (ANL), and Oak Ridge National Laboratory (ORNL). Facility directors are given freedom to allocate resources between accelerator development and other activities.

For a number of reasons the development of future accelerator capabilities has generally been given lower priority in BES and NP than in HEP, which is the only program that has a specific budget category for funding

accelerator R&D and other technology development. These reasons include less program office encouragement for proposals addressing accelerator development, tight budgets, user community pressure, and lower expectation by the DOE that money be spent on this. Many NP and BES facilities are part of larger, multipurpose laboratories that have Laboratory Directed Research and Development (LDRD) funds that can be used for proposal development, and this has been done successfully in a number of cases.

The response of BES to the recent National Research Council (NRC) study on FELs gives an example of the opportunities that can be missed absent a clear long-term accelerator research policy. The NRC study contained a number of recommendations related to accelerator R&D. Synchrotron radiation facility directors have the freedom to respond to these recommendations, but BES has no expectation that they will and no policy about the appropriate nature or level of response. In addition, university and national laboratory researchers who are not associated with synchrotron radiation facilities have no clear way of securing funding for research in these directions. A promising program for developing a low-cost infrared FEL, initially supported by the Strategic Defense Initiative Office, was discouraged from applying for BES funding. Work on short wavelength FELs is minimally supported. Leadership in this field is in danger of moving from the United States to Europe and Japan where such FEL facilities are planned and user communities are growing.

High Energy Physics. The distinction between HEP and the other programs is the expectation by the HEP program management and the user community that some money be spent on long-range, risky accelerator development even if it comes at the expense of running time, construction of experimental apparatus, or other laboratory services. Development for future accelerator capabilities has a priority comparable to other laboratory goals, and pursuing these developments is evaluated on par with other goals when

reviewing a facility. As in BES and NP, directors of HEP facilities are also given freedom to allocate resources between accelerator development and other activities.

High Energy Physics is the only program that supports long-term accelerator R&D as a matter of policy. The High Energy Physics Advisory Panel (HEPAP) Subpanel on Accelerator Research and Development (M. Tigner, chair) concluded in 1980 that support for long-range accelerator development was critical for the future of high energy physics. This was reaffirmed in 1994 by the Subpanel on Vision for the Future of High Energy Physics. This support manifests itself in two ways: (1) long-term accelerator development at major high energy physics laboratories, and (2) a proposal-driven, peer-reviewed program in accelerator physics that supports long-term R&D activities relevant to HEP by investigators at universities, national laboratories, and industry. This policy is strongly supported by the DOE Division of High Energy Physics.

Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (Fermilab), Argonne National Laboratory (ANL), and Stanford Linear Accelerator Laboratory (SLAC) have high energy physics accelerator R&D supported as part of the annual funding of the laboratory by the DOE. These programs have varying combinations of support for specific (present and future) projects and for more general research. In addition, a program administered through the HEP division accepts proposals for accelerator R&D and evaluates them through the peer review process. This program has been effectively managed, and it significantly broadens the opportunity for innovative developments that will have substantial long-range impact. Some of the research at ANL, LBNL, and BNL is also evaluated and funded through this peer review process. In total, about 2.5% of the FY1995 HEP operating budget was devoted to this program.

The HEP support of accelerator R&D follows from the link between advanced accelerator capabilities and HEP scientific frontiers. The expectation that HEP laboratories pursue future facilities aggressively follows from this close link. The centrally administered program leads to accelerator activities outside of the national laboratories, particularly at universities, and activities within national laboratories but outside those relating to operating or developing facilities.

Universities are a central element of the basic research enterprise in the United States. The combination of academic freedom and education has proven to be a creative force that is an effective way to train future leaders. The proposal-driven, peer-reviewed program that HEP runs is an important way for a university scientist to obtain accelerator research support, and for accelerator physics to have the creativity and leadership needed for the future. The program is a major source of funding for accelerator physics research and graduate student training at universities.

The Office of Fusion Energy (OFE) supports R&D in fusion science and technology to achieve its principal mission, fusion energy production. Accelerators play important roles in fusion research as energy and neutron sources. OFE also has stewardship for basic plasma science, which has significant synergism with long-term accelerator research.

The OFE funding of accelerator R&D is predominantly driven by its programmatic needs. Because fusion research has a significant technology development component, much of the effort funded by OFE can be properly considered R&D. Short-term R&D is managed by the individual facilities using resources provided to them by the OFE. Medium-term research to develop future accelerator capabilities and long-term research has traditionally been managed and funded by separate technology development branches within

OFE. In addition, OFE has a proposal-driven peer-reviewed program of long-term accelerator R&D in support of inertial fusion.

In recent years OFE has suffered from a series of funding crises. This situation has had serious consequences for its accelerator based programs and ultimately, perhaps, for the nation. As a result, several promising R&D efforts have fallen victim to erratic funding and shifts in program priorities. For example, OFE developed neutral beam accelerators for plasma heating which were later discontinued. Since the United States no longer has a program in this field, leadership has moved to Japan. Similarly, the development of accelerators for fusion materials testing was stopped a decade ago but is now being resumed in an international collaboration.

The history of the Heavy Ion Fusion (HIF) Program provides an example of the difficulty of nurturing spin-off accelerator technology programs that may hold great promise for the nation. Although HIF has been strongly endorsed by the Fusion Energy Advisory Committee (FEAC), the National Academy of Sciences (NAS), and the Fusion Policy Advisory Committee, the DOE has found it difficult to find a hospitable long-term home. HIF has been transferred back and forth between OER and Defense Programs (DP), ultimately landing in OER, where it has been shuffled between HENP, BES, and OFE. Clearly, more coherent management is essential for efficient progress in an R&D program.

Assessment of Management of Short and Medium-Term Accelerator R&D

The heads of OER accelerator facilities are responsible to the DOE and the facility users for providing the capabilities needed for their experiments (short-term R&D). They must also develop future accelerator-based capabilities envisioned as important to the evolution of the facility and host

laboratory (medium-term R&D). The current approach to short-term accelerator R&D in which the program is managed by the facility is effective. The Subpanel agrees with the DOE approach that facility managers are best able to choose the most appropriate R&D for construction, operations, and improvement within their overall budgets determined by DOE/OER program management.

In general, accelerator facility managers can and do devote resources for development of future capabilities (medium-term R&D), particularly in HEP. In the face of tight budgets, user pressure, and less encouragement by the DOE, the development of future accelerator capabilities has generally been given lower priority at BES and NP facilities. Where these facilities are part of a larger, multipurpose laboratory, the availability of LDRD funds can and has offset this limitation.

The Subpanel endorses the present system of accelerator R&D directed at future capabilities, which is supported by funds from facility budgets. However, we believe that this approach could yield additional benefits if the BES and NP programs were to more explicitly recognize the value of such investments and evaluate the performance of their accelerator-based facilities accordingly.

Assessment of Management of Long-Term Accelerator R&D

Based on the Subpanel's work, it is clear that long-term generic R&D is vital to the future advances in accelerator technology required to fulfill some critical aspects of the scientific mission of OER. While this statement is generally accepted in principle, the realities of funding and of the OER management structure can lead to problems. Accelerator R&D efforts that are perceived as of no immediate benefit for the core mission are often handled on

an ad hoc basis and are most susceptible to funding uncertainties in times of financial stress. Generic accelerator R&D which spans the OER offices or does not have direct relevance to a mainstream program may be orphaned and not receive the consideration it deserves. As a result, the OER programs may fail to capitalize on opportunities for tapping innovative ideas, for developing new long-range technologies and for training and education of the next generation of accelerator scientists and engineers.

The importance of this long-term research presents a particular dilemma to facility directors who already bear responsibility for short and medium-term R&D. Examples of major DOE user facilities and centers and those sciences they serve are:

- Fermilab, SLAC, and the Alternating Gradient Synchrotron (AGS) at BNL for high energy physics.
- Continuous Electron Beam Accelerator Facility (CEBAF) and the Relativistic Heavy Ion Collider (RHIC) at BNL for nuclear physics.
- SSRL, the Advanced Photon Source (APS) at ANL, the Advanced Light Source (ALS) at LBNL, and the NSLS at BNL for materials science, chemistry, biology, etc.

Do the directors of those facilities and laboratories bear some responsibility for the development of accelerator technologies for the future of these scientific fields? We believe that they do and note that the National Research Council FEL study has argued similarly for the specific case of FELs. Moreover, the intellectual challenges and research opportunities associated with longer-term developments are important for attracting and keeping the most creative engineers and scientists. The Subpanel believes that facility directors

will continue to address some aspects of long-term R&D, but that a broader based effort is required.

The 1980 Tigner HEPAP Subpanel recognized the importance of accelerators to HEP research and recommended a coherent program of long-term R&D in accelerators. The Subpanel report led to the creation of the HEP Advanced Technology R&D program which has successfully demonstrated the benefits of such an approach. *Our composite Subpanel discussed at length the question of whether OER offices beyond HEP should fund accelerator research and development other than that at facilities. Such funding is necessary if these programs are to meet their scientific missions, impact national needs, benefit from the creativity at universities and national laboratories other than those hosting specific facilities, and contribute to the education of the scientists and engineers who will be needed to build and operate future facilities. As accelerators have become increasingly vital to research in NP, BES, OFE, and OHER, there is a similar need for long-term accelerator R&D as an essential component to carry out the mission of these OER programs. Such research supports both the scientific goals of the program and the health of the accelerator technology required for the future. It is essential that these programs include planning and funding for needed long-term accelerator capabilities if they are to accomplish their mission.*

The Subpanel recommends several modifications to the present OER management approach for long-term accelerator R&D to assure that each program includes it as part of its research portfolio. The Subpanel has considered a number of mechanisms to enhance the level of long-term accelerator R&D and has identified the following characteristics that are essential for successful broadening of such activities within OER programs:

- A) The funding process should be proposal driven and peer reviewed and be open to all qualified researchers based at universities, in industry and at the national laboratories.
- B) Proposals should explicitly include the potential impact on the OER missions and the benefit to the nation.
- C) Proposals should be reviewed by peers with appropriate knowledge of accelerators and by scientists from the relevant office in OER who have vision and understanding of the long-range directions and needs of OER and of the nation.
- D) Each program office should have expertise on accelerator issues to assure appropriate management input. This expertise could come from detailees with accelerator experience when the program office has a limited staff size and accelerators are a relatively small part of the office activities.
- E) Each program office should develop and update regularly a broad list of accelerator research and development topics relevant to future aspects of the program mission and other national needs.
- F) OER and its programs should publicize their intention to consider accelerator research and development proposals to be evaluated within these guidelines.

The Subpanel strongly believes that each OER program should have or participate in a proposal-driven, peer-reviewed process to encourage, evaluate, and fund long-range accelerator R&D that is relevant to its mission and to broader national needs. We believe that the Director of the OER is in

the best position to determine the most effective management approach to implementing this long-term accelerator R&D program and should do so.

Funding

To estimate present levels of funding for accelerator R&D, the Subpanel gathered information from the major DOE, NSF, and university accelerator facilities, and from DOE program managers. Short-term R&D on existing facilities is so closely connected with on-going operations that it is difficult to quantify. Similarly, R&D on approved construction projects frequently includes some small-scale, longer-term R&D efforts. Because of these ambiguities, the Subpanel has not attempted to estimate funding for short-term R&D. In FY1995, funding for medium-term accelerator R&D was approximately \$32M from OER programs and \$10M from DP. OER funding for long-term accelerator R&D totaled approximately \$16M with \$12M from HEP, \$2M from OFE, and less than \$1M each from NP and BES. OHER funded no accelerator R&D.

This Subpanel believes that enhancing long-term accelerator R&D is in the best interests of the DOE OER programs and the nation. The appropriate level of investment for this activity will vary from program to program depending on overall priorities, funding level, and other program dependent considerations. The Subpanel views the OER advisory committees as the appropriate mechanism to determine the optimal level of investment in long-term accelerator R&D. Hence, we recommend that the Director of Energy Research charge the OER advisory committees with recommending the appropriate level of funding for each program. For this to be effective, each advisory committee should include or consult accelerator experts. This recommendation should be taken by each advisory committee in view of the totality of the program for which it is responsible. Thus, each advisory

committee, with input from its OER office, would take into account the evolving nature of each program and its mission within budget constraints and requirements for balance. Such advice has already been provided by HEPAP in the form of the Tigner Subpanel recommendation.

This Subpanel would like to provide a guideline for the advisory committees indicating the level of investment in proposal-driven, peer-reviewed long-range accelerator R&D that the Subpanel believes would assure that OER continues to meet its accelerator related stewardship responsibilities in all program areas. We suggest that HEP continue to use the Tigner report, which recommended an investment of 4% of the HEP operating budget as a healthy goal. This investment has been as high as 3.2% and is currently about 2.5%. Recognizing that different OER programs need different levels of long-range accelerator R&D, we suggest the following as a funding basis for the NP, BES, and OHER investments in accelerator-based research: (1) for Nuclear Science Advisory Committee (NSAC) and Basic Energy Sciences Advisory Committee (BESAC), respectively, the NP and BES accelerator operations budgets, and (2) for Health and Environmental Research Advisory Committee (HERAC), the OHER budget for development and support of experimental facilities at the BES accelerators. Even though it is the belief of the Subpanel that the ultimate level of funding in this area has to be determined by each Advisory Committee in view of the totality of the program for which it is responsible, the Subpanel suggests that roughly 1% of this annual basis is a reasonable initial level of investment for long-term accelerator R&D. If this investment is made, U.S. science and technology will benefit in the long-term.

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VII. CONCLUSIONS AND MAJOR RECOMMENDATIONS

The study and assessment conducted by this composite Subpanel has focused on the role of accelerator science and technology in enabling critical capabilities to support the mission of the U.S. Department of Energy (DOE) Office of Energy Research (OER) programs and to contribute to important national interests. Accelerator science and associated technologies nurtured by DOE's OER programs continue to be an essential part of DOE's energy research mission, especially in the fields of high energy and nuclear physics. In the basic energy sciences accelerator-based facilities and techniques are playing increasingly vital roles in the characterization and modification of materials. Accelerator-related technologies have played an essential role in fusion research. The health and environmental sciences make use of accelerator-based facilities for the study of biological structures and other significant research. These trends will continue. High energy and nuclear physics will continue to rely on state-of-the-art accelerator facilities, and the basic energy sciences and health and environmental research programs increasingly will use accelerator facilities to expand their scientific and technical horizons. For fusion energy, the use of accelerator-based drivers is one of the promising roads to commercial power in the next century.

This Subpanel believes that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have *de facto* held a national trust for the stewardship of accelerator science and accelerator-based technology development. This role has provided the foundation for essential capabilities needed both to fulfill the DOE mission and to address broader national interests. Although there have been many very significant contributions to this field made by researchers supported by other government agencies and by other nations, the Subpanel was led to this point of view by:

- the high level of investment in accelerator science and technology by the Atomic Energy Commission (AEC), Energy Research and Development Agency (ERDA), and DOE,
- the sustained level of commitment, and
- the number and impact of the developments that have resulted from this support.

This Subpanel has concluded that it is vital that the DOE and its OER programs explicitly acknowledge that they hold a national trust for accelerator science and technology, and that this trust and the resulting stewardship responsibilities should be an explicit part of the overall DOE OER mission. This conclusion was formed and strengthened by our hearing and considering detailed information from the DOE OER program offices, from other parts of the agency, from the accelerator science community, and especially from a panel of highly regarded researchers whose collective vision spans the full range of the OER mission.

Given the vital role that OER's programs have and should continue to play in the nurturing of accelerator science and technology, the Subpanel has formulated the following recommendations:

Recommendations

- A. Stewardship of accelerator science and technology should be acknowledged as an explicit part of the overall DOE OER mission.**

This stewardship entails:

1. Design, construction, and improvement of accelerator-based facilities needed to carry out the mission of DOE's energy research programs.
2. Effective utilization and operation of these accelerator-based facilities.
3. Support of the accelerator R&D required to provide facilities at the technological cutting edge for the sciences that they serve.
4. Appropriate investment in basic accelerator science and in related technology R&D to form the foundation for capabilities needed in the future.
5. Support for the training of the accelerator scientists and engineers required to provide the accelerator-based capabilities needed in future years.
6. Support for the continued development and maintenance of the basic tools needed to stay at the cutting edge in the accelerator field (e.g., computer codes, essential stand-alone test facilities, and critical infrastructure elements at the accelerator-based facilities).

B. Each OER program should have proposal-driven, peer-reviewed long-range accelerator R&D as part of its research portfolio.

The following guidelines are essential for the success of this approach:

1. The funding process should be open to all qualified researchers based at universities, in industry, and at the national laboratories.
2. Proposals should explicitly include the potential impact on the missions of OER programs and the benefit to the nation.
3. Proposals should be reviewed by peers with appropriate knowledge of accelerators and by scientists from the relevant office in OER who have vision and understanding of the long-range directions and needs of OER and of the nation.
4. Each program office should have expertise on accelerator issues to assure appropriate management input. This expertise could come from detailees with accelerator experience when the program office has a limited staff size and accelerators are a relatively small part of the office activities.
5. Each program office should develop and update regularly a broad list of accelerator research and development topics relevant to future aspects of the program mission and other national needs.

6. OER and its programs should publicize their intention to consider accelerator research and development proposals to be evaluated within these guidelines.

The Director of the Office of Energy Research is in the best position to determine the most effective management approach to implementing this long-term accelerator R&D program and should do so.

To assure that this R&D is well targeted, program managers should actively consult both their scientific communities and the accelerator community about the long range opportunities that could be enabled by forefront development in accelerator science and technology.

C. The Director of the Office of Energy Research should charge the appropriate OER advisory committees with recommending the level of long-term accelerator R&D funding for each program.

This recommendation should be taken by each advisory committee in view of the totality of the program for which it is responsible. Thus, each advisory committee, with input from its OER office, would take into account the evolving nature of each program and its mission within budget constraints and requirements for balance. These advisory committees should include or consult accelerator experts.

D. The current approach to short-term, facility-directed accelerator R&D should be continued.

Facility management is best able to choose the most appropriate R&D for the construction, operation, and improvement of facilities within overall facility budgets determined by DOE/OER program management.

E. The present system of medium-term R&D directed at future capabilities of interest to laboratories, facilities or users of facilities should be strengthened.

The Subpanel endorses the present funding of medium term accelerator R&D by facility budgets and Laboratory Directed R&D (LDRD) funding. However, additional benefits would be gained by each program office explicitly recognizing the value of such investments and evaluating the performance of their accelerator-based facilities accordingly. In the DOE reviews of accelerator laboratories and facilities, the charge should include assessment of the medium and long-term accelerator R&D.

In all accelerator R&D improvements suggested in the above recommendations, informal coordination among OER program offices should be fostered.

F. OER program officers and laboratory managers who are responsible for the stewardship of accelerator science and technology should make a special effort to nurture societal applications.

Associated with OER's stewardship of accelerator science and technology is a responsibility to encourage the timely distribution and diffusion of this knowledge and technology. To be effective this requires an environment which fosters communication and cooperation between OER-funded research institutions and the industrial and commercial sectors.

A related issue is the treatment of long-term spinoff technology development that does not fit the DOE program structure. For example, the management of the Heavy Ion Fusion program has been a thorny issue for years, primarily because of indecision regarding its home within the DOE. Our concern is that crucial opportunities for the DOE and the nation could be missed unless the management structure is capable of sustained commitment to such long-term technology developments.

From the information gathering process and during the deliberations of this Subpanel the very important contributions of this field to basic scientific research and to society as a whole were again underscored in a dramatic way. While the areas mentioned in the recommendations presented above need attention, the Subpanel finds that accelerator science and technology is a vital and intellectually exciting field. It has provided essential capabilities for the DOE/OER research programs with an enormous impact on the nation's scientific research, and it has significantly enhanced the nation's biomedical and industrial capabilities. Further progress in this field promises to open new possibilities for the scientific goals of the OER programs and to further benefit the nation.